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Transmon SUS Telescope Alignment Procedure

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Table of Contents

Figures

Abstract

This technical note describes an alignment procedure for the Transmon SUS Telescope that uses a combination of an autocollimator for initial coarse alignment, and a Shack-Hartmann wavefront sensor for fine alignment. The telescope is part of the Transmon Suspension System for aLIGO.

1 Introduction

The purpose of this technical note is describe an alignment procedure for the ETM Telescope that uses a combination of an autocollimator for initial coarse alignment, and a Shack-Hartmann wavefront sensor for the final fine alignment. The telescope is part of the Transmon Suspension System for aLIGO.

A preliminary design layout of the Transmon Suspension with the folded ETM Telescope placed below the Transmon optical table is shown in Figure 1.

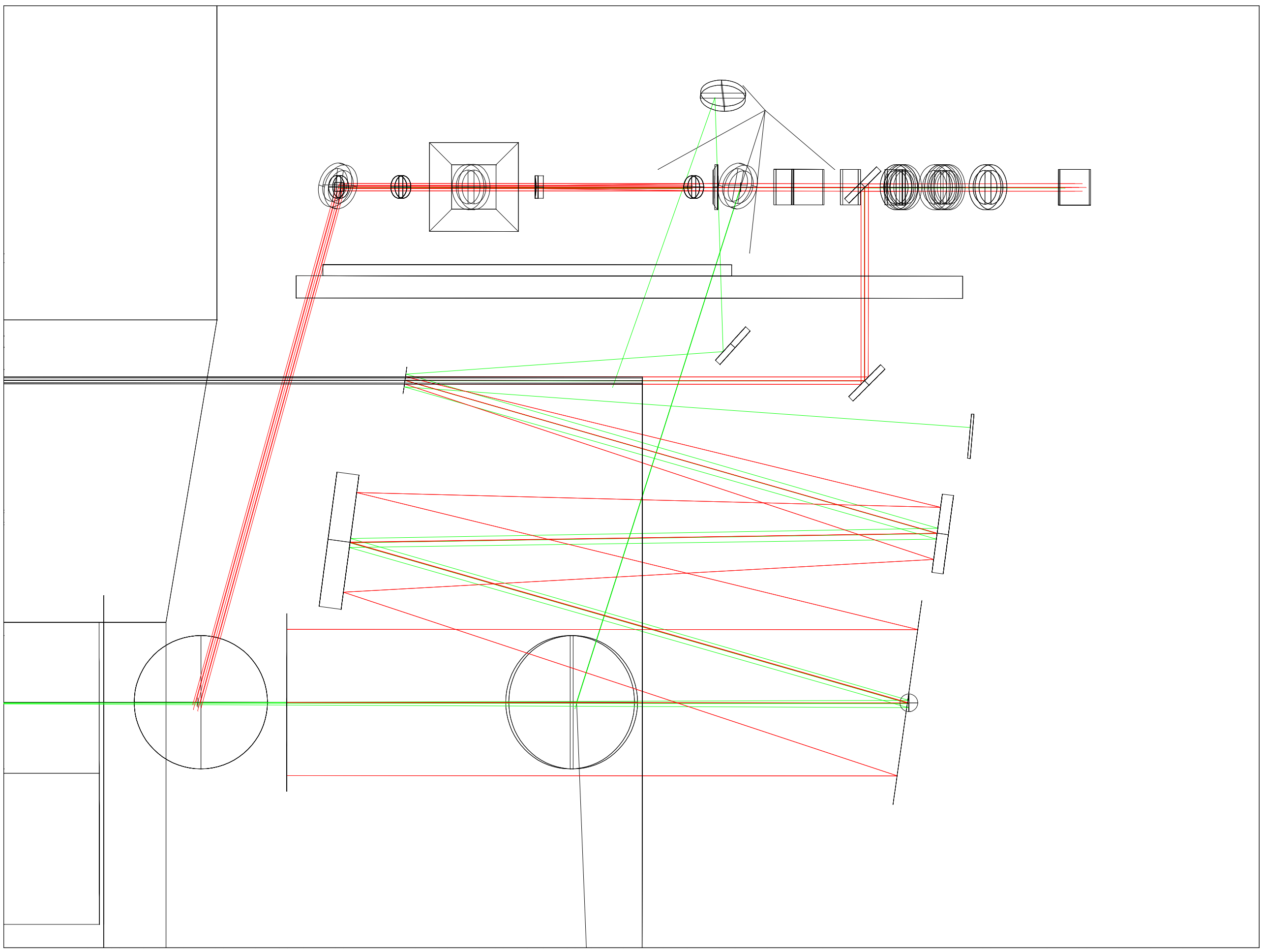

Figure 1: ETM Transmon SUS Telescope

1.1 Off-axis Parabolic Design

An unfolded ZEMAX layout was used to analyze the performance of the off-axis parabolic telescope, shown in Figure 2. The primary focal length is 2000 mm, and the secondary focal length is 100 mm. The off-axis distance for the primary is 562.2 mm, and for the secondary is 28.1 mm.

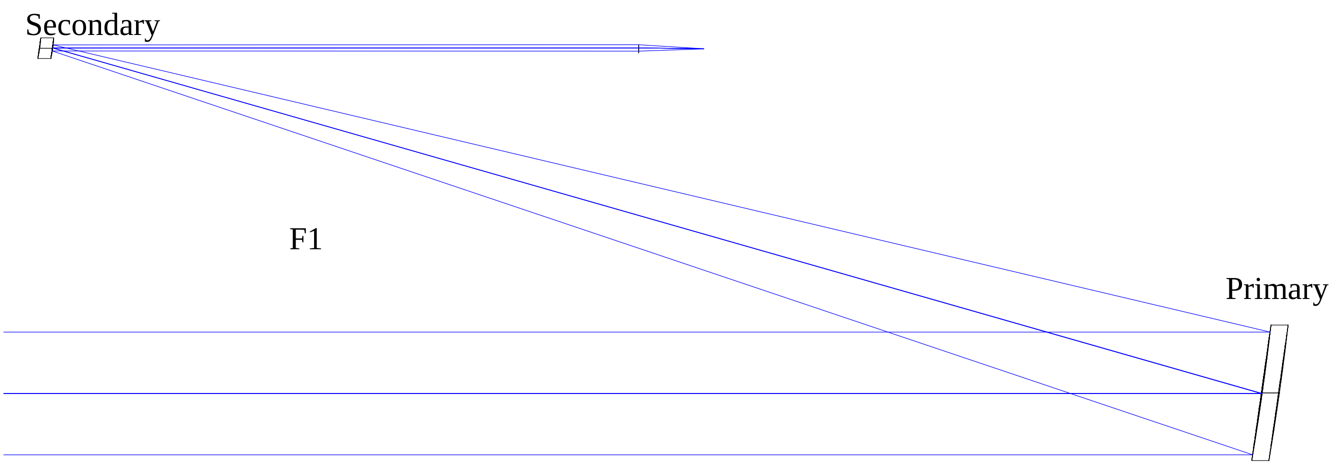

Figure 2: ZEMAX model of off-axis parabolic telescope

1.2 Manufacturing Tolerance of the Off-axis Parabolic Mirrors

The surface irregularity of the parabolas is specified to be < 1/8 wave @ 633 nm wavelength. This is equivalent to an irregularity of < 1/13 wave @ 1064 nm.

The tilt tolerance of the mechanical axis of the mirrors to the optical axis is +/- 0.0083 deg.

The decentering tolerance of the primary mirror is +/- 1 mm, and the decentering tolerance for the secondary mirror is +/- 0.3 mm.

The focal length tolerance of the primary mirror is +/- 20 mm.

2 Alignment Procedure

2.1 Secondary Mirror Translation and Tilt Correction

Satisfactory alignment of the telescope can be accomplished by moving only the secondary mirror in five degrees of freedom—tilting in pitch and yaw, decentering vertically and horizontally, and moving along the optical axis for focus.

The primary mirror will be placed in a fixed mirror mount whose mechanical axis is pre-aligned to within 0.1 mrad of the reference optical axis of the telescope. The rms combined error of the mirror mount and the tilt error of the primary is 0.01 deg.

The secondary mirror has the necessary degrees of tilt and translation freedom.

2.2 Autocollimator and Shack-Hartmann Instruments

Either an autocollimator beam, or a collimated light source, such as a laser or a super luminescent diode, will be injected into the secondary end of the telescope along the optical axis, as shown in Figure 3. The beam will reflect from a mirror when it emerges from the primary mirror and be reflected back through the telescope and emerge after a round trip at the secondary mirror. The beam splitter shown in the enlarged view will reflect a portion of the return beam to the cross-hairs of the autocollimator or to the Shack-Hartmann wavefront sensor.

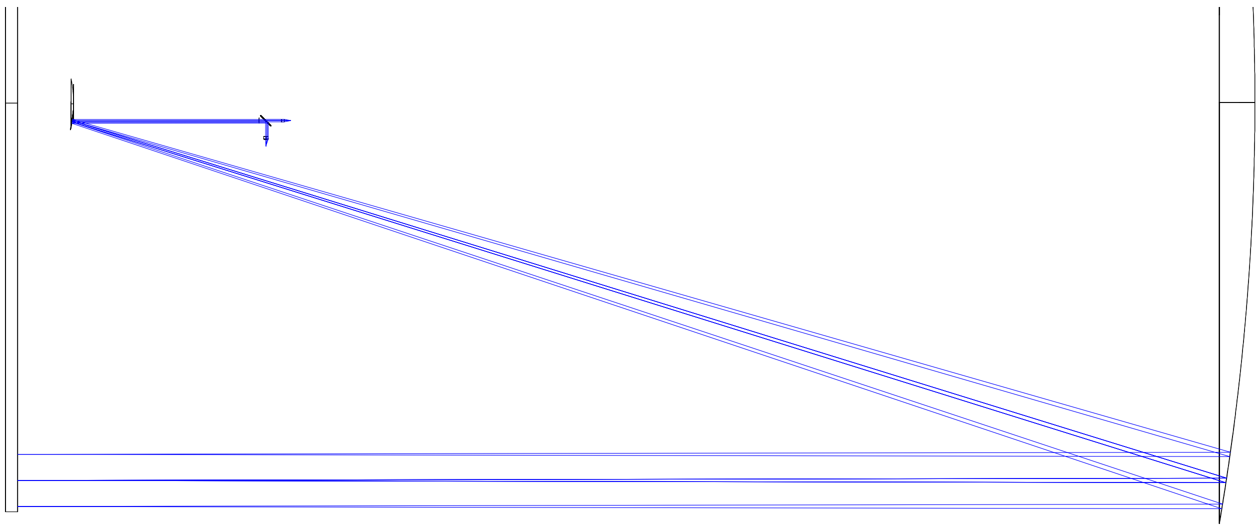

Figure 3: Double Pass Alignment Beam

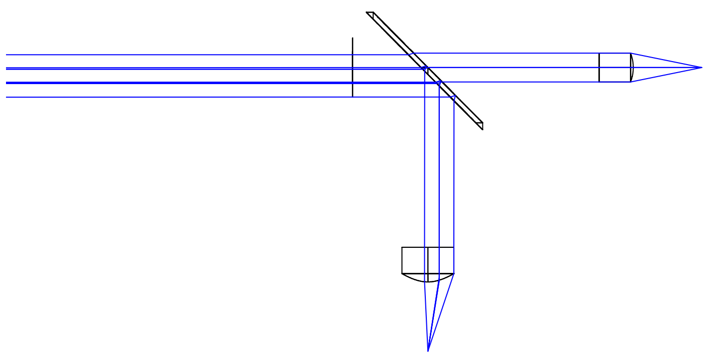

Figure 4: Pick-off Beam Splitter for Returned Beam Sensing

2.3 Initial Mechanical Alignment of Primary and Secondary Mirror Mounts

The ETM Telescope structure provides a reference surface whose normal defines the direction of the input and output optical axes of the telescope. The primary and secondary mirror mounts are pre-aligned parallel to the reference surface.

2.3.1 TMS Telescope Input Axis

Establish the input axis of the TMS Telescope by placing a collimated light source, such as a laser pointer or a second autocollimator, at the center of the entrance aperture. Align the collimated light source so that it is perpendicular to the reference surface of the ETM Telescope structure.

2.3.2 Placement of Primary Mirror

Place the primary mirror of the telescope with the barrel centered on the input axis, and the back surface parallel to the reference surface. This is the permanent location of the primary mirror.

2.3.3 Placement of Secondary Mirror

Place the alignment autocollimator at the output end of the telescope (small end) on the output beam axis and perpendicular to the reference surface.

Turn on the autocollimator beam. Place a reference mirror against the mounting surface of the secondary mirror mount and use the reflected autocollimator beam to align the secondary mirror mount perpendicular to the autocollimator beam. This will force the back of the secondary mirror to be parallel to the reference surface.

Turn off the autocollimator beam.

Insert the secondary mirror. The input axis beam should hit approximately in the center of the secondary mirror.

Translate the secondary mirror laterally until the input axis beam that reflects from the secondary mirror enters the autocollimator and is centered on the autocollimator cross-hairs as viewed through the eyepiece.

This procedure establishes the rough alignment of the telescope mirrors.

2.4 Coarse Alignment with Autocollimator

During this procedure, the secondary mirror will be translated laterally and longitudinally, but will not be tilted.

Place an autocollimator at the output (small end) of the telescope, perpendicular to the reference surface with the projected beam pointing toward the secondary mirror. The autocollimator beam will traverse the telescope and exit through the input aperture.

Remove the input axis light source and place a large mirror at the input aperture with the mirror surface parallel to the primary reference surface to reflect the autocollimator beam back through the telescope.

1. Initial focus is achieved by moving the secondary mirror longitudinally until the returned reticle pattern seen in the eyepiece of the autocollimator has sharp edges. After initial focus

is achieved, it will be observed that the reticle pattern is not centered with the crosshairs of the autocollimator, which have been previously set parallel with the optical axis of the telescope.

2. Next, the reflected autocollimator beam is aligned with the optical axis by translating the secondary mirror transverse to the beam until the reticle pattern is centered on the cross hairs.
3. The focus and beam pointing steps are iterated until the reticle pattern is visually in sharp focus and is centered on the cross hairs.

2.4.1 Initial Misalignment Conditions

The ZEMAX wavefront map in Figure 5 shows the initial aberrations of the wavefront of the telescope beam with the following worst case combination of tilt and de-center errors of the primary and secondary mirrors:

Primary

tilt	0.01 deg
decenter	1 mm

Secondary

tilt	0.01 deg
decenter	-0.3 mm

Defocus -20 mm

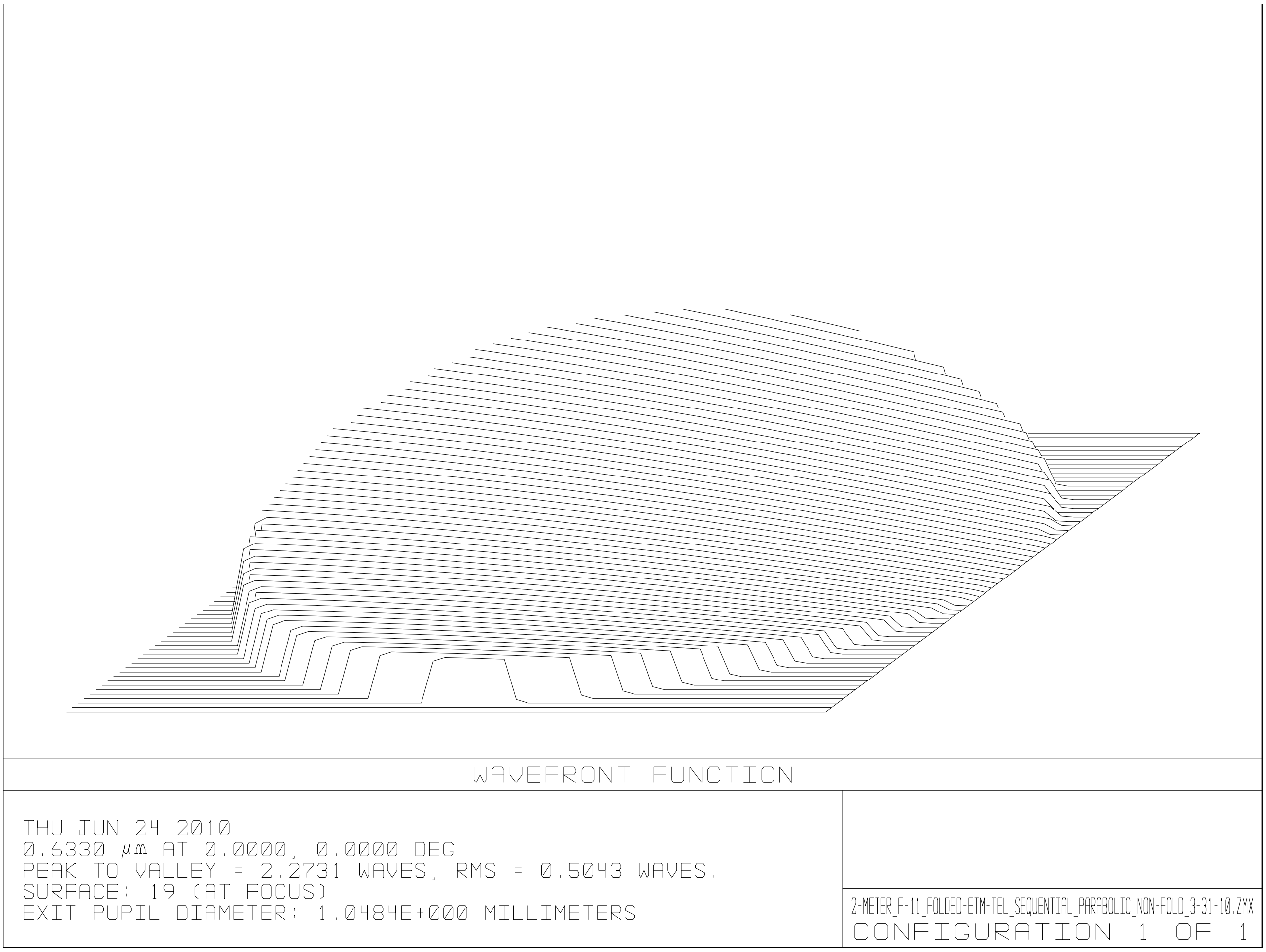

Figure 5: Initial Misalignment Conditions without focus error

2.4.2 Best Alignment with an Autocollimator

The resulting wavefront map after visually focusing and subsequently centering the reticle pattern on the cross hairs of the autocollimator is shown in Figure 6. However, it should be emphasized that this alignment was done by ZEMAX using a large number of trials seeking to minimize the wavefront distortion. The simple approach of focusing the reticle pattern by observing visually the sharpness of the edges will not achieve as good an alignment.

At best, this approach will result in a diffraction-limited the wavefront, but still exhibits a certain amount of astigmatism as seen by the saddle shape of the wavefront map in Figure 6. The astigmatic beam shape is exposed in the spot diagram of Figure 7. The black circles represent the Airy's disc diameter, and are approximately located 1 Rayleigh range before and after the focused spot. The spot diagram implies that the astigmatic foci are within the Rayleigh range of the telescope secondary beam, and may be problematic for the operation of the Transmon SUS system.

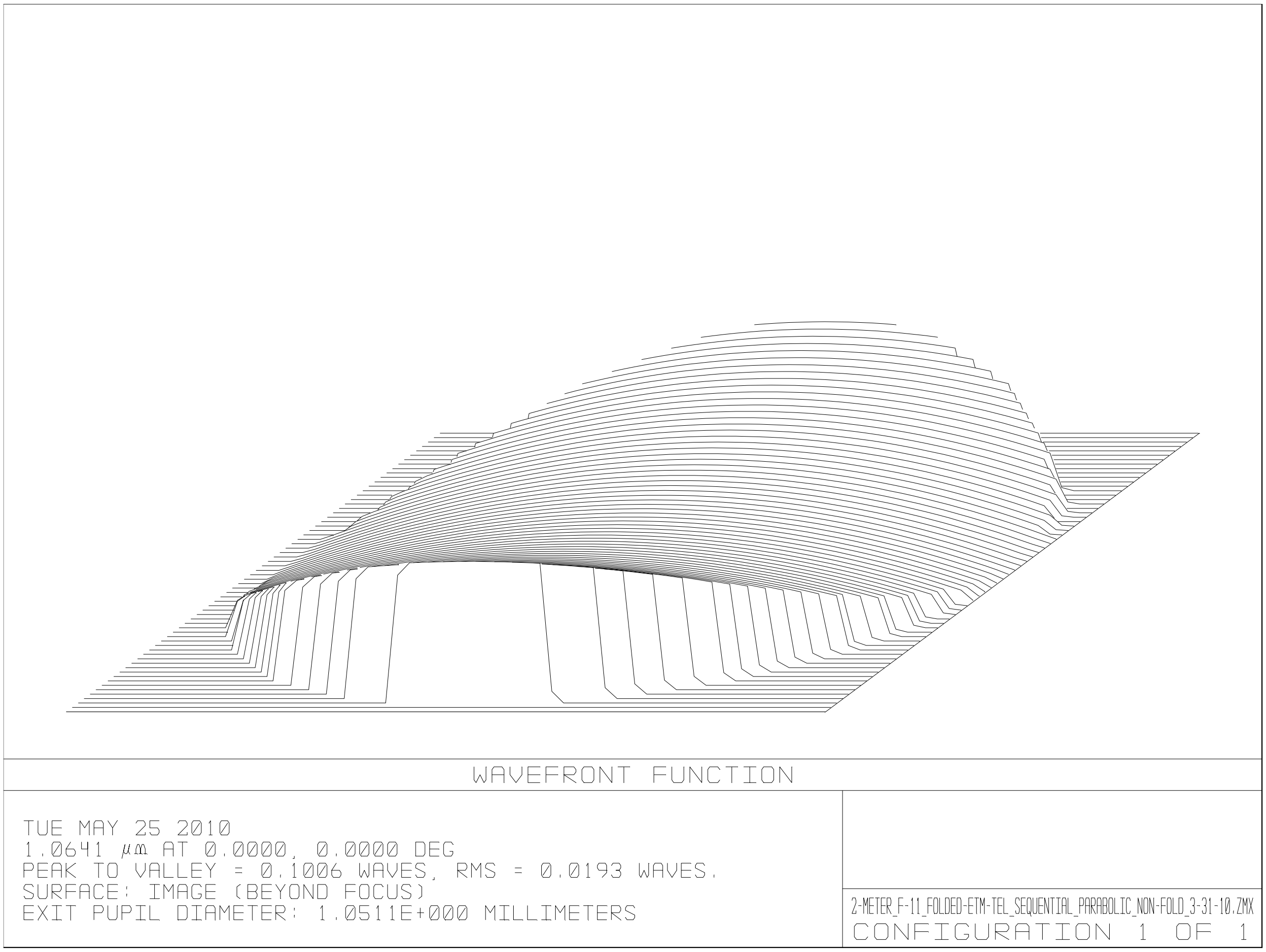

Figure 6: Wavefront after Alignment with the Autocollimator, 3-degrees of Freedom of Secondary Mirror

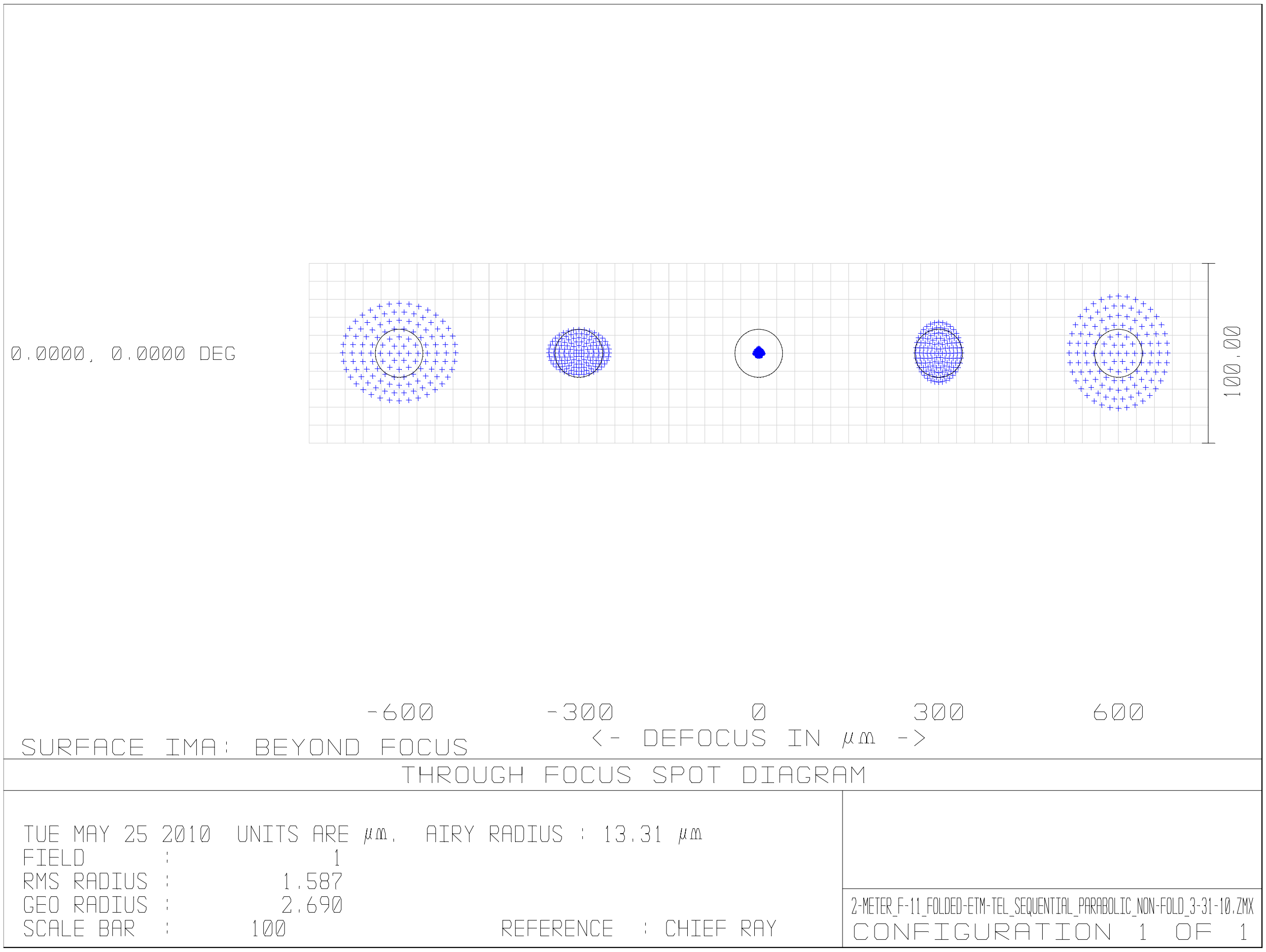

Figure 7: Spot Diagram after Alignment with Autocollimator

2.5 Alignment with the Shack-Hartmann Sensor

The wavefront distortion and the resulting astigmatism can be minimized by allowing the additional degrees of freedom of tilting the secondary mirror. The Shack-Hartmann sensor is needed to provide a direct measurement of the wavefront map, and to provide a quantitative tool for aligning the five degrees of freedom of the secondary mirror position, which would be impossible to do with the autocollimator.

The resulting ZEMAX alignment using five degrees of freedom is shown in Figure 8. The wavefront aberration is < 0.004 waves, which is less than the specified 1/13 waves wavefront irregularity for the individual telescope mirrors.

The spot diagram in Figure 9 also shows negligible astigmatism.

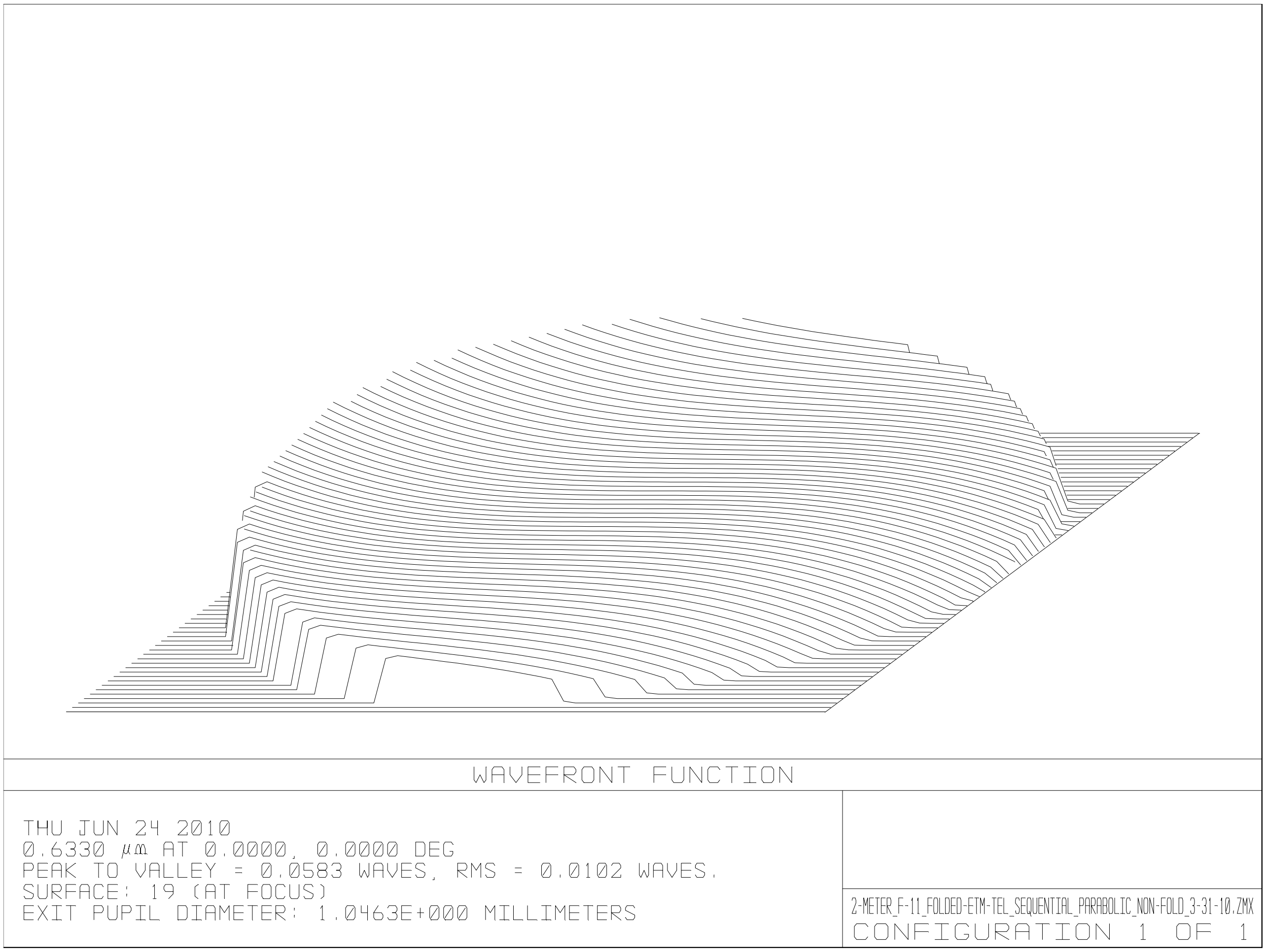

Figure 8: Alignment Using Five Degrees of Freedom of Secondary Mirror

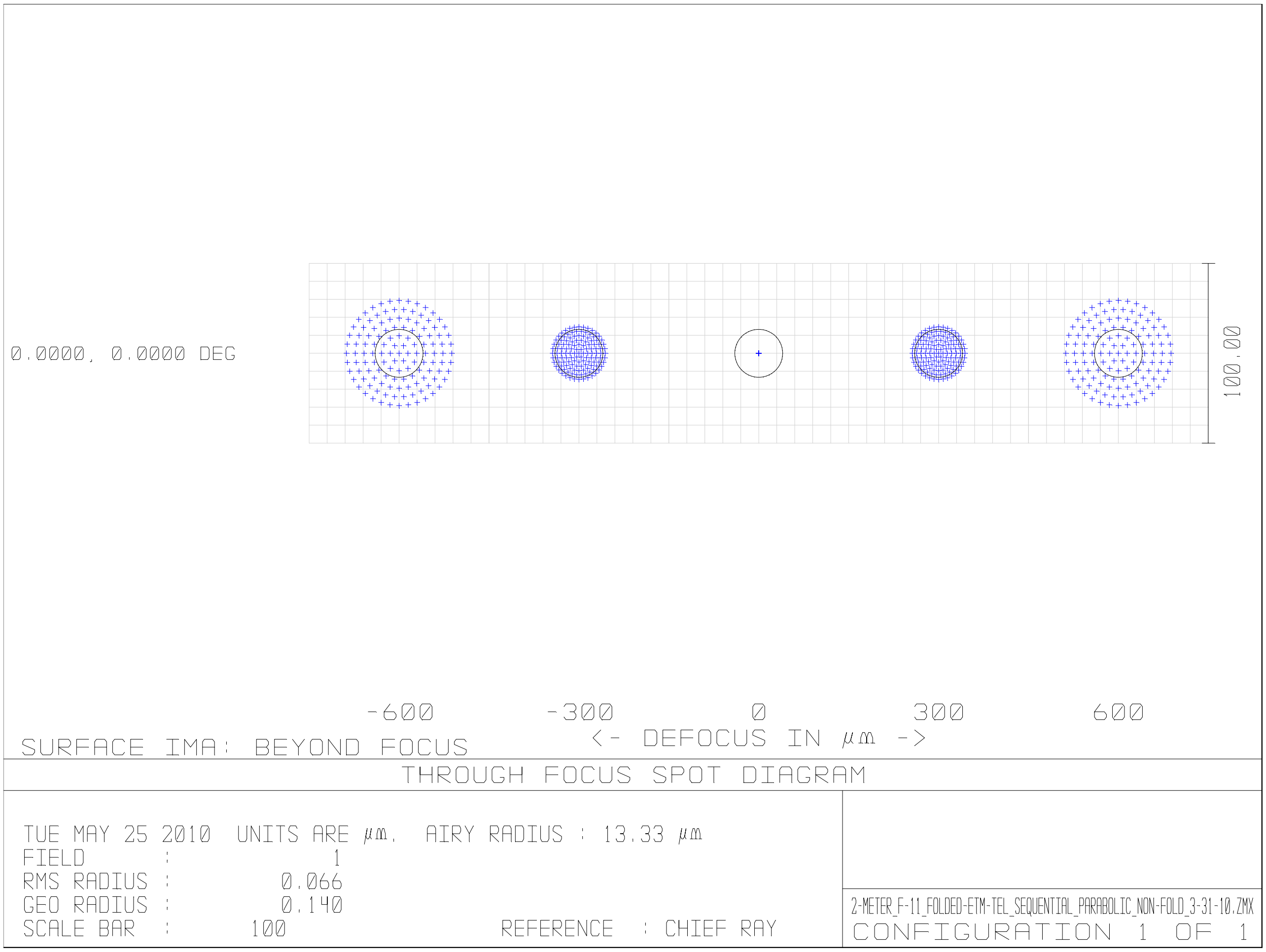

Figure 9: Spot Diagram, after Alignment Using Five Degrees of Freedom of Secondary Mirror

2.5.1 Commercially Available Shack-Hartmann Sensor

A screen capture of the output of a commercial Shack-Hartmann sensor is shown in Figure 10. It provides quantitative data of the wavefront distortion in terms of Zernike coefficients.

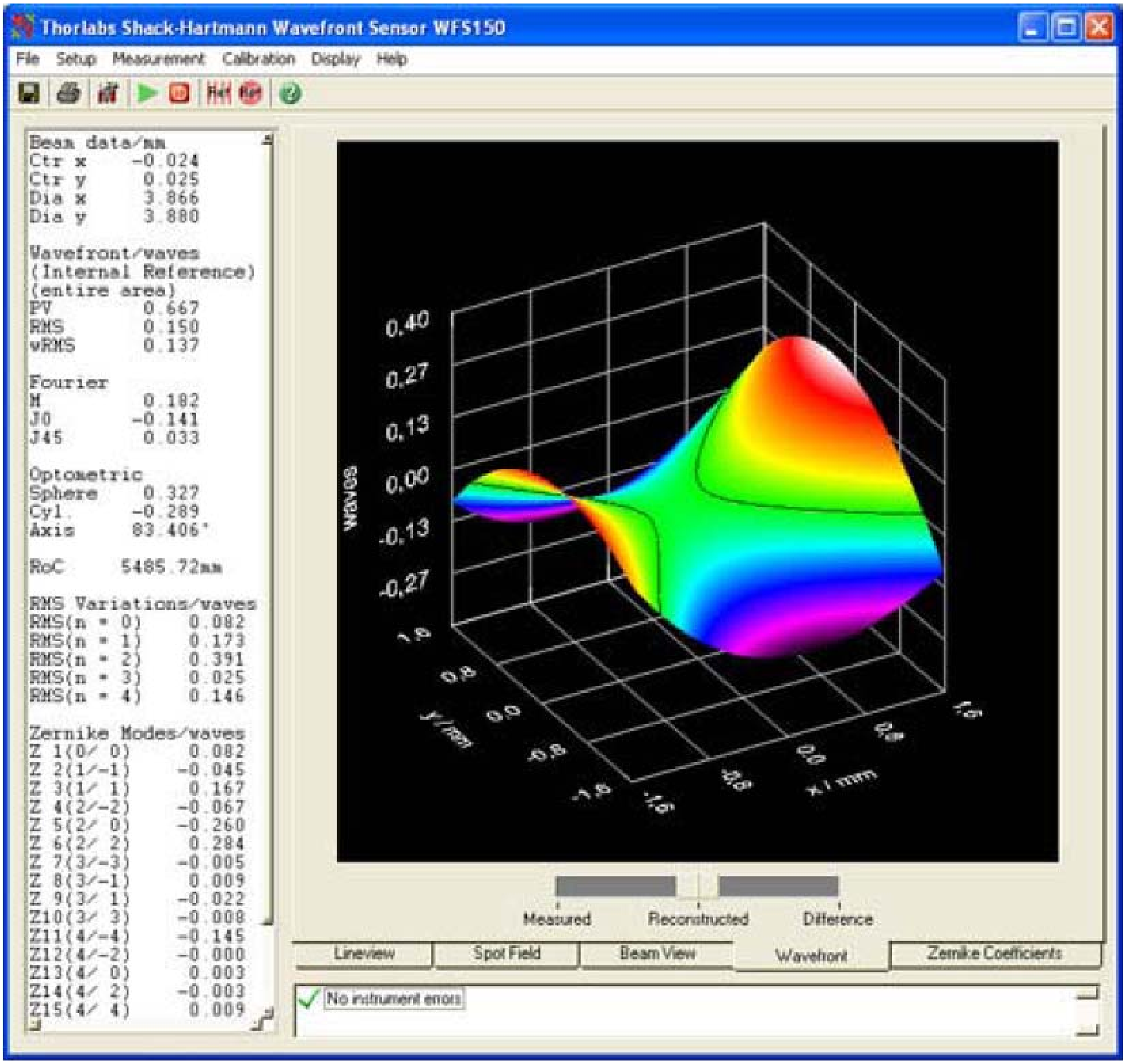

Figure 10: Wavefront Map from Shack-Hartmann Sensor